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Stabilization of Clayey Soils Using Non-Traditional Aggregates: A Review

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Abstract The bibliographic review carried out contemplated the studies performed for the chemical stabilization of clayey soils, which can be problematic due to their deficiency in physical and mechanical properties in construction. The studies included in the following article were born from the initiative to seek new alternatives to the use of cement and lime, particularly in the reduction or elimination of their use as traditional stabilizers, as well as to better manage the disposal of industrial waste. The incorporated studies evaluated stabilization by geopolymerization, reinforcement, use of common additives with other aggregates and residues. Stabilization effectiveness is measured primarily by results in physical properties such as optimum moisture content (OMC) and maximum dry density (MDD), both obtained through compaction tests and mechanical properties through tests such as unconfined compressive strength (UCS) and bearing capacity (CBR). To a lesser extent, the study of improvements related to durability, flexibility, permeability, among others, is also contemplated; studies, despite improving the main properties of the soils, deepened their research to obtain more information on the stabilization of clayey soils.

Keywords Stabilization, Geopolymerization, Fibers, Residues, Additives

1. Introduction

Large amounts of clay soils can be found in the world; they cover a large part of the earth's surface, more than 70% of the surface of India, 10% in Syria and a large part of Ethiopia [1] [2] [3]. In Latin America, it is known that the capital of Colombia built its foundations on this type of soil [4] and in Argentina problems are reported in structures erected on expansive soils [5]. Clay soil tends to be problematic, being soft and expansive [6], the former is unsuitable due to its high compressibility and low shear strength [7]; the latter causes damage to structures because of swelling-shrinkage behavior in the presence or absence of moisture [8]; and in general, they present, a change in volume when frozen by frost [9]. In spite of this, large constructions are built on these soils having to carry out rectification projects as a consequence of their instability and behavior, causing great expenses all over the world [10]. Therefore, it is necessary to consider mechanical or chemical stabilization to improve the properties of problematic soils [6].

Stabilization of this type of soil has been carried out since the 1960s with the main objective of improving shear strength and controlling volume variations [11]. Studies have commonly been conducted on the use of chemical additives to improve the performance of soft and expansive soils forming a more solid foundation; being the most common: cement, lime, fly ash and granulated blast furnace slag [6]; but nowadays, it is necessary to look for eco-sustainable materials, economical and capable of developing performances equal or even better than common binders; for this reason, alkaline activated materials have been a viable option according to literature [11].

It was Joseph Davidovits, a scientist from France, who first coined the word "Geopolymer", referring to an inorganic aluminosilicate material created with silica and alumina precursors; geopolymerization being the production of a chain composed of repeating units of silicon oxide and silicoaluminate formed from residues and alkaline activators [12].

The geopolymer is produced by creating aluminosilicate gels, which tend to bond with fine clay particles forming a cementitious matrix; that is, a pozzolanic reaction is formed with the help of calcium silicate hydrate (CSH) or calcium silicoaluminate hydrate (CASH) gels [13]; where the chemical composition and particle size influence the pozzolan reaction; presenting greater reactivity in fine particles that present larger specific surface areas [14]; and having as an advantage the reduction of pollution by replacing cement with alkaline binders formed from geopolymers [15], which constitutes an environmentally sustainable option; being necessary for its implementation alumina-silica precursors [16]. Geopolymerization can also involve natural pozzolans, which come from volcanic sources or sedimentary clays; these are better than Portland cement in terms of lower energy consumption and, therefore, are more sustainable in the life cycle of road constructions [13] [17]. In this process, structures composed of silica and alumina are formed, which guarantees an improvement in resistance related to a decrease in porosity, thus forming a denser structure [15].

Likewise, improvements in the properties of clayey soils are achieved by the addition of fiber. It has been observed that fibers reinforce the soil by interlocking with the particles, acting as binding components, which improves the cohesion and frictional strength of the soil, resulting in improved load-bearing and strength properties [18]. In relation to this, the addition of residual plastic of different types has been investigated, where an improvement in compressive strength was observed; a result linked to the development of the tensile strength of the plastic and the friction generated with the soil particles [19]. Other fibers such as straw, rice husk and bamboo fibers have been successful in reducing the swelling index value due to the reduction of soil mass [20], in addition to decreasing the plasticity index and increasing the strength [8].

Common construction materials, such as cement, generate large amounts of CO_2 and high construction costs. In view of these disadvantages, the use of residues for soil improvement is proposed; these residues can be minerals or come from industrial waste. In this way, the aim is to save on construction materials and reduce the demand for them [21]. It is important to consider other effects since not only geopolymerization and reinforcement make possible the improvement of soil properties. On the other hand, it has been observed that the mere addition of other elements such as calcined clay contributes to the increase of the maximum density; the cause being the filling of pores, thus minimizing the empty spaces between soil particles [22]; also the presence of minerals such as quartz, with the addition of igneous rock dust has contributed positively in high plasticity clays; because this mineral is not cohesive and does not retain moisture; concluding that the addition of elements with hydrophobic minerals can have an impact on the decrease of the plasticity index (PI) and activity of soils [23]. The same effect is reported with the use of glass powder and other residues [24].

This article performs a literature review, with the purpose of evaluating the mechanisms of chemical stabilization of clay soils classified as CH or CL. The mechanisms observed for soil improvement are: geopolymerization, through the use of some alkali for the formation of cementing agents; reinforcements, constituted by recycled plastic fibers and organic fibers; incorporation of common additives (lime, cement, fly ash and granulated blast furnace slag) with other non-traditional aggregates and wastes. Additional effects related to the decrease of Atterberg limits and pore filling are included in studies that use different residues and compounds that manage to improve the physical and mechanical properties of the soil without necessarily being pozzolans, but result in a double benefit by eliminating the problem related to the accumulation of residues.

2. Stabilization in Problematic Soils

The success of stabilization depends not only on the aggregate or mechanism used, but also on the soil as a binder which, together with the other additives, interacts depending on their composition and distribution [13]. For this reason, an experienced geotechnical engineer must determine advantages and disadvantages of using different types of stabilizers in problematic soils that threaten structures because of uplift, cracking and collapse. Here subgrades, which support roads or highways, can be contemplated [25].

Stabilization by means of additives has a positive impact because, unlike mechanical stabilization, it is economical, does not require much labor and generates a long-lasting and permanent effect. In addition, a large number of studies have corroborated its compatibility with various types of soil [1].

When soil is stabilized, the moisture content will always be lower in amended samples than in undisturbed samples. High moisture content is one of the main reasons why the bearing capacity decreases, so moisture removal could improve the strength and stability of expansive clayey soils [25] [26]; another reason is the volume changes in this type of soils, these can be predicted by the initial conditions such as moisture content, degree of compaction and operating stress [27].

The need for stabilization by means of aggregates is evident, also taking into account that expansive soils have greater repercussions in areas with seismic vulnerability due to the loss of shear strength caused by the pressure between cracks and spaces; and reduction in the effective stress after earthquake movements [28]. To solve these problems, it is necessary to take into account that the effects of stabilization are also determined by the main constituents of the soil and the curing time used [25].

2.1. Chemical Stabilization by Geopolymerization

In geoplimerization, it is important to use pozzolans that exhibit silicon, aluminum and iron oxide contents in a percentage greater than 70% of the total mass. The pozzolanic activity in these materials will define the final structure in the stabilization composed of hydrated calcium silicates and aluminates, it will also depend on the reaction rate and the maximum amount of pozzolan that can be combined with calcium hydroxide $Ca(OH)_2$ [13].

The most commonly used alkali is sodium hydroxide (NaOH); this is a white, odorless, non-combustible reactive compound. In stabilization, Na+ and OH- ions react with minerals in clay soils to modify their properties. Its addition to soils with organic material has been studied where it has positive implications since NaOH has better resistance to failure in the wet state compared to other commonly used additives and the increase in its concentration decreases the liquid limit (LL); but its main benefit is the increase in soil density with the aid of compaction [29].

Similarly, other studies recommend the use of sodium silicate to optimize the geopolymer reaction phase [30]. Sodium silicate corresponds to the common name of the chemical compound denoted by $Na_2(SiO_2)nO$, with sodium metasilicate (Na_2SiO_3) being the best known variation [31]. Thus, the combination of NaOH and Na_2SiO_3 is used to favor precursor activation [32]. However, the use of a single alkaline activator such as sodium metasilicate is also rescued due to the unfeasibility and difficulty of workability due to the danger and corrosive potential of the traditional two-component activation synthesis [33]. Consequently, it is observed that the improvement of strength is related to the molarity and concentration of the activating and binder solution, respectively [28]. It is necessary to point out that due to the exothermic reaction involved in the use of alkalis, it is necessary to let them cool at room temperature [28] for 24 hours [32].

Factors to be taken into account are temperature, length of cure time and activator proportions. Studies describe the advantage of high curing temperatures for stabilization with geopolymers. The most commonly used curing temperatures tend to be higher than 20 °, even higher and with greater positive effects on the improvement of soil properties. When cured at room temperature, the resistance is influenced by the molarity of the alkali, the type of precursor or additive and their ratio; since the use of higher amounts of alkali contributes to the release of aluminum and silica ions, accelerating polymerization [28] [31].

Table 1 shows the main chemical compounds found by the researchers when using different aggregates; in addition to the alkaline implemented. The mentioned investigations address important aspects for the use of geopolymers, such as temperature, age and curing conditions; and sulfate resistance.

Table 1. Stabilization by geopolymerization

Reference	Aggregate	Chemical Composition				Alkalis
		CaO	SiO_2	Al_2O_3	Fe_2O_3	
[15]	Metakaolin	0.13	57.16	37.71	1.28	Calcium carbide slag
[16]	Ground granulated blast furnace slag	34.19	40.42	10.6	1.28	NaOH and Na_2SiO_3
	Class F fly ash	4.24	57.2	24.4	7.1	
[28]	Wastepaper sludge ash	72.2	16.4	6.8	0.77	NaOH and Na_2SiO_3
[30]	Ground granulated blast furnace slag	45.45	29.96	12.25	0.52	NaOH and Na_2SiO_3
	Class F fly ash	4.3	51.11	25.56	12.48	
[31]	Ground granulated blast furnace slag	30.81	34.25	12.3	1.44	NaOH and Na_2SiO_3
	Ordinary Portland cement	62.55	19.82	4.83	3.6	
[32]	Ground granulated blast furnace slag	35.3	34.5	16.7	1.5	NaOH and Na_2SiO_3
	Fly ash	2.32	53.04	34.7	2.53	
[33]	Class C fly ash	27.37	35.3	17.26	6.02	Na_2SiO_3
	Class F fly ash	6.87	53.51	19.67	10.24	
	Ground granulated blast furnace slag	33.76	41.47	12.9	0.61	
[34]	Bagasse ash	4.9	74.6	8.93	4.2	NaOH and Na_2SiO_3
	Quarry dust	3.07	70.41	17.41	4.51	
[35]	Recycled glass powder	11.69	65.23	2.23	0.45	NaOH
	Copper slag	3.11	31.99	6.68	35.11	

The use of the precursor metakaolin (MK) is present in several investigations corroborating its good performance; and, analyzed in relation to the temperature and age of curing with calcium carbide slag as activator, it was reported that compared to cement it is less susceptible to low temperatures (-2 ℃ and -10 ℃) which is beneficial in permafrost regions or low temperature environments; strength development is due to silica-alumina structures generated from the erosion and dissolution of the MK surface by the alkaline environment where SiO_4^{4-} and AlO_4^{5-} are released, which in the presence of Ca^{2+}, form calcium silicate hydrate (CSH) and calcium aluminate hydrate (CA-H) [15].

Sometimes, handling alkaline compounds results in an exothermic reaction that can be dangerous for those in charge of stabilization, in response to this, another alternative to the conventional method known as mechanochemical activation is offered, which consists of the preparation of the additive in dry state by grinding the main aggregates, then mixing with water and subsequent incorporation into soil samples with optimum moisture content [16]; this method, apart from providing safety in the procedures [33], improves the performance in terms of resistance due to the improvement of reactivity, reduction of particle size and improvement of surface area; this improvement and the use of ground granulated blast furnace slag (GGBS) have been shown to be effective against magnesium sulfate attack [16]. These results are important nowadays, since the rapid growth of society leads to an increase in industrialization and therefore to a greater contamination of soils, so it is necessary to evaluate the durability of soils, which can be eroded by water contaminated with sulfates, clayey soil stabilized with cement is ineffective, and researchers even mention that it can disintegrate and become similar to loose sand due to the neutralization of the CAH and the formation of expansive crystals such as ettringite, which can destroy the internal structure, generate porosity and seriously damage the samples; On the other hand, with the combined use of slag and activated fly ash, no considerable sulfate damage is observed, only flaking and micro-cracks [32].

The precursors used can also have a low calcium content, such as fly ash (FA), in geopolymerization, here the hydroxyl ions of the alkaline activator facilitate the decomposition of aluminosilicate oxides that form gels that subsequently harden between the soil particles, thus improving their properties and having sodium aluminum silicate hydrate (N-A-S-H) as the final product; which is advantageous since precursors with a lot of calcium could promote the formation of ettringite, which in contact with sulfates, generates changes in volume and problems in the treated soil. With the use of FA, the sulfate resistance of samples with prolonged curing periods, 90 and 365 days, does not show noticeable volumetric changes, which is related to the absence of expansive products; with respect to resistance, geopolymerization with fly ash and slag show improvements even with curing in sulfate solutions [30].

Regarding curing, it can be performed in dry and wet conditions; and depending on the chosen condition, the soil will present different variances in the change of mass and volume. It has been seen that the use of only activators did not have great significance and its behavior after stabilization is the same as untreated soil samples in both curing conditions; likewise, using only cement and GGBS in dry curing conditions affects a high change in volume, for curing in dry conditions; however, when using cement, GGBS and alkaline activators (ratio 1: 1) better results related to mass and volume changes are observed for both curing conditions, concluding that the integration of activator and precursor is necessary [31].

An analysis under humid conditions (20%-30%) was also contemplated, with the objective of simulating real field situations, considering sodium metasilicate as activator and GGBS, class F and C fly ash as precursors for stabilization. The presence of water is essential to dissolve the activator; when moisture is insufficient, undissolved activator particles are detected and form dark spots on the samples. Dry activation depends on medium to high moisture content to strengthen soft soils. Better strength development is demonstrated by incorporating GGBS with class C fly ash in contrast to class C fly ash, class F fly ash and their combination in wet conditions [33].

To counteract the absence of slag and fly ash due to the drop in production in the steel industry, waste such as paper sludge ash, a by-product of paper recycling, activated with hydroxide and sodium silicate, is studied; whose implementation had better benefits than cement in the same proportion (10%), regarding the UCS resistance through the generation of NASH gels in highly expansive clays; and in general, the samples meet the requirements of cement treatment for stabilizing subgrade with paper sludge ash, especially using a molarity of 12M or more for the preparation of activators. This treatment also involved a reduction in the potential for swelling and water absorption of more than 90% [28]; for expansive soils, there was also evidence of better performance of precursors with low Cao content such as bagasse ash and geopolymerized quarry dust where the q_u (ultimate strength) showed better development and the soil samples were less fragile than when class F fly ash was used with the same treatment; from this result, the improvement in the performance of soil samples under dynamic loads was deduced [34].

Another commonly used additive is recycled glass, and studied together with copper slag, it was shown that the latter has better contributions to the Atterberg limits, since it notably reduced the liquid limit; and compaction parameters, due to the higher density of the copper slag that increased the maximum dry density; while crushed glass increased the UCS value to a greater extent due to the greater amount of silica and alumina in its composition [35].

With the analysis of different geopolymerization studies, different effects of geopolymerization (formation of C/NASH gels, pore filling, increase in maximum dry density, decrease in LL, PI and optimal moisture content) and the mechanisms (quantity are confirmed and relationship of precursors, type of alkaline(s); molarity; time, type and curing conditions) that make possible the improvement of clay soils of low or high plasticity, including expansive soils.

2.2. Stabilization by Reinforcement

With additives such as cement, lime, among other plastic additives that increase stiffness; natural or artificial fibers are used to improve flexibility [19] and load-bearing capacity, being able to contemplate the oriented or random fiber method for their incorporation [1]. As in the previous additives, the excessive use of reinforcements can have an effect contrary to the objectives of stabilization such as reducing the strength of the soil. In subgrades with clayey soil, traffic loading generates tensile stress, which can cause excessive bending at the surface; therefore, the feasibility of adding fibers to improve stiffness, strength and load-bearing capacity, in addition to flexibility, is considered [19] [36] [37].

Table 2 shows different fibers and their characteristics, which were studied by authors around the world with the incorporation of other residues or traditional binders to stabilize problematic clay soils.

The point load test shows that strip reinforcement improves strength because of the friction generated with soil particles, with minimal incorporation in either untreated or lime-treated soils. Incorporation of Polypropylene Terephthalate (PET) waste reduces the optimum moisture content and maximum dry density (MDD) due to the lower specific gravity of this material (1.3) compared to soil (2.78) [19] [37] [20]. The plastic in the form of 1 mm thick sheets at different depths of the soil samples (H/2 and H/3), being H the height of the samples, shows an improvement in CBR values and load distribution [1]. Being corroborated the good performance of the plastic, PET fibers are studied at room temperature under freezing and thawing conditions; this fiber is inert, so it is not affected by the temperature in the freeze-thaw cycles [39]. However, these fibers did not prevent strength reduction since these cycles deteriorate the contact between soil particles (friction is weakened). A contribution of the addition of this fiber is the inhibition of large cracks due to the bridging effect offered by the reinforcement [37]. PET fibers are also added taking into account the fragility due to active cracks in tensile and shrinkage behavior in expansive soils; characteristic of stabilization by means of aluminosilicate and alkaline precursors (geopolymerization), according to this, this addition (alkaline binder and PET) had a great effect on the samples; increasing the CBR value by 19% and reducing the deformation of the soils in comparison with the use of lime with the same reinforcement; which demonstrates the effectiveness of geopolymerization with reinforcement in the improvement of mechanical properties [36]. With the addition of plastic residues, the swelling problem is dissipated; with a 2% addition the OMC decreases about 19%, the UCS value increases up to 2.41 times and the internal friction increases; all this with 8x15mm fibers [20]. For expansive clayey soil with cellulose-based fibers either from bamboo, rice husk and wheat straw; it evidences different improvements such as the imporvement of the UCS in more than 90%, decrease in the plasticity index and reduction of the free swelling index; these changes were influenced by the size (150-300 μm) and quantity considered (15%) [8].

Table 2. Stabilization by reinforcement

Reference	Residues or Traditional binders	Fiber	Length-Width (mm)	Thickness (mm)	Gs
[1]	-	Plastic sheets	-	1	-
[8]	-	Bamboo	0.3	-	-
	-	Rice husk	0.3	-	-
	-	Wheat straw	0.15	-	-
[18]	-	Rice husk	0.425	-	-
	-	Saw dust	0.425	-	-
[19]	Lime	Polyethylene Terephthalate	30-3	0.2	1.3
[20]	-	Solid plastic wastes	8,15,25 – 5,8,15	-	-
[36]	Alkaline binder	Polypropylene	0.033	-	0.9
[37]	-	PET	25-10	0.25	1.35
[38]	Lime and silica fume	Coir geotextile	80-0.02	-	-
[39]	Pond ash	Polypropylene	12-0.018	-	-
[40]	Hydrated lime	Tire-derived aggregate	1,67 a 3,34		1.10-1.11
[41]	Brick powder	Plastic strips	10-1	-	-

Lime and silica fume have been investigated in stabilization with good results; therefore, coconut fiber geotextile was treated with these compounds and added to clay soil samples, where the swelling percentage in the samples was reduced by 70% and the CBR increased by approximately 400% in a single layer of the lime-treated geotextile. Silica fume was less influential in soil improvement compared to lime [38].

Polypropylene fiber is also used to prevent tensile cracking as the main purpose; as it is an inert material, it is durable. With the use of non-combustible coal residue (pond ash), calcium silicate hydrate (CSH) is produced which increases the UCS values with the solid matrix formed even under freeze-thaw cycle; adding polypropylene fiber contributed slightly to the improvement; even the strength decreased when the addition went beyond 1%. The addition of pond ash increased the brittleness in the samples; at this point, the polypropylene fiber played an important role in improving the tensile strength thanks to the increase of the interfacial interaction of the soil particles with the 0.5% addition as a limit; beyond this percentage it was unfavorable [39].

The addition of tire-derived aggregate, which went through a shredding process and had the wire removed, in the form of small particles along with hydrated lime was evaluated in the clayey soil on compaction properties, compressive strength and swelling potential. The results for optimum moisture content and maximum dry density decreased as the percentage addition of waste tire fiber increased. The values in the UCS test had a rise and subsequent fall. To counteract this, lime was an ideal additive for increasing strength due to cation exchange and particle flocculation-agglomeration. The added fiber shows exponential improvements for the reduction of swelling potential, by more than 80%, as its percentage of addition increased [40].

Previous studies have considered rice husk ash as an option for stabilization; however, due to environmental concerns, rice husk fibers are being studied. Another useful waste is saw dust; this fiber is intended to generate friction due to its irregular surface. The use of this type of fiber involved its treatment with citric acid to reduce its biodegradability. Rice husk and sawdust fibers increased the UCS and Triaxial test values becoming similar with 4% and 6% content of each fiber, respectively. In the analysis, the fiber interlacing process improved shear strength and stiffness. It should be noted that the best performance was obtained with sawdust, but both options exceed the values of the control samples; except in the MDD values [18]; the opposite is the case when using brick dust and residual plastic strips where the density increases. And the swelling, characteristic of expansive soils, reduces with a minimum content of plastic strips of 0.75%, an amount that also influenced the improvement of CBR and UCS values; with the help of brick dust [41].

2.3. Chemical Stabilization with Common Additives and Other Non-Traditional Aggregates

Since stabilization with lime, cement and fly ash have become common additives; in addition to the slag that has been presented to solve geotechnical problems related to the stabilization of clayey soils [42] [43]. Different contributions are presented with these common additives with other non-traditional aggregates, which gave positive results in the stabilization matter.

2.3.1. Lime and Non-Traditional Aggregates

Normally, lime is used because of its low cost compared to other binders [25]. Lime can be used to improve the strength and workability of expansive clayey soil, since its use reduces the diffuse double layer of particles, which limits the changes in volume due to the high CaO content [44]. Soil samples need more water as their content increases for hydration; this combination results in an exothermic reaction where water evaporates [45]; the main effect after adding lime being the increase of OMC and the decrease of MDD [46] [23] [2].

When this traditional additive is added, chemical reactions such as cation exchange, flocculation and pozzolanic reaction are expected; where the calcium hydroxide releases silica and alumina; lime reacts with water and clay particles, in a process called cation exchange, replacing silica-alumina ions with calcium ions; thus calcium silicate hydrate (CSH) or calcium silicoaluminate hydrate (CASH) cementitious gels are formed due to the release of silica and alumina. Cation exchange contributes to changes in soil plasticity; which has a reaction potential due to the negative charge it possesses; this in turn contributes to flocculation, which is the binding of clay particles [13] [46].

Table 3 shows aggregates that were used with lime to stabilize clayey soils, considering their chemical composition and inherent properties of the aggregates.

Table 3. Stabilization with lime and other aggregates

Reference	Aggregate	Chemical Composition (%)				Gs	pH
		CaO	SiO_2	Al_2O_3	Fe_2O_3		
[2]	Natural pozzolana	8.5	46.5	19.28	11.22	2.85	-
[23]	Igneous Rock: granite and rhyolite	-				2.71-2.74	-
[44]	Phosphogypsum	57.2	6.81	0.203	0.382	2.216	2.3
[46]	Waste ceramic dust	-	-	-	>10	2.81	-
[47]	Nanoclay (NC)	1-2nm				-	-
	Glass fiber	-					

Phosphogypsum is a waste obtained from the manufacture of phosphoric acid; it was used to study its contribution to the improvement of physical properties of expansive clayey soils; however, it did not have a significant effect despite producing cementitious gel and pozzolanic reactions, so lime was incorporated to meet the strength and bearing capacity required at the beginning, being 4% lime and 30% phosphogypsum the proportion that manages to improve the strength by more than 7 times compared to the untreated soil [44]. Igneous rocks such as granite and rhyolite have also been used for soil stabilization with lime, for which it was necessary to establish an alkaline environment with a value greater than or equal to 12.4, which is achieved with 6% lime. The tests carried out on the samples indicated a decrease in PI with granite and rhyolite powder of more than 20%. A particularity is that, while lime increased the OMC values, igneous rocks decreased it, which would mean a lower humidity to reach the higher density. Also, the CBR and UCS values increased, which is attributed to the higher density of the rock powders that reduced the porosity. The best results were observed with the use of rhyolite due to its structure and mineralogy [23].

The small size of some aggregates can be beneficial because they have a larger specific surface area. For this reason, the use of nanoclay (NC) is feasible for stabilization. The improvement of the strength improvement factor (SIF) in combination with lime has been proven. The soil-mix effectiveness improved, as a 28-day equivalent marl soil stabilization was achieved with exclusive use of lime in only 7 days at 1% content; then, with this optimum percentage of (NC), glass fiber (0.75%) was incorporated; obtaining an additional improvement of the SIF [47].

Expansive soils can support pavements, which will be subject to cyclic loading, presenting deficiencies in their properties, as well as in their workability. As previously reported, lime increases the OMC and decreases the MDD, while the residual ceramic powder (WCD) has an opposite effect, namely the MDD increases with the addition of lime and the fixed amount of 15% WCD. The results indicate that, with respect to CBR, 3% lime has an effect that is equivalent to using 10% WCD; corroborating the increase in CBR values [46].

Adding lime to a high plasticity clayey soil has a positive effect on plasticity, reducing the PI by more than 20%. A natural pozzolana (NP), finely divided material that can have a cementitious effect because it is a siliceous material and/or aluminum, can be used to counteract the decrease in MDD to which lime leads. NP alone achieves increasing bearing capacity; but the performance together with lime in the CBR test is considerably better. Combining these two aggregates results in improved physical (OMC and MDD) and mechanical (CBR) properties [2].

2.3.2. Cement and Non-Traditional Aggregates

Soil plays an important role in cement stabilization, the initial condition of soils with fine particles influences the improvement of their properties; it is evident that, in organic clays of medium to high plasticity, pozzolanic cement is also effective [26].

Geopolymerization is the chemical process for the use of geopolymers while for cement it is hydration. Water content is important to ensure proper hydration and strength formation. For this reason it is necessary to consider curing in wet conditions over dry conditions to obtain a greater gain in unconfined compressive strength. Normally using lime significantly reduces the liquid limit, this effect is not evident with cement [31] [48].

Considering all of the above, Table 4 shows non-traditional aggregates; these were evaluated and different results were obtained according to their efficiency in soil stabilization.

In order to take advantage of rice husk, which constitutes an agro-industrial waste, rice husk ash, which contains silica, was studied as a pozzolanic material in combination with cement to stabilize clayey soils of high and low plasticity, here the mentioned mixture absorbed water from the clayey soil; which was important to improve the bearing capacity [26]. Wood ash can also be considered as an alternative use, since it comes from renewable resources, and it also exceeds the pozzolanic activity index indicated by ASTM c618. Its addition reduces the Atterberg limits, especially the liquid limit; and with respect to strength, it increases with different wood ash contents, however, since cement reacts faster, strength decreases with high ash contents [48].

Table 4. Stabilization with Cement and other aggregate

Reference	Aggregate	Chemical Composition (%)				Gs	pH
		CaO	SiO_2	Al_2O_3	Fe_2O_3		
[25]	Calcium chloride	$CaCl_2$					
[26]	Rice husk ash	1.29	89.09	1.75	0.78	-	-
[48]	Firewood Ash	0.61	59.35	7.48	3.78	-	-
[49]	Nano silica	-				2.87	6.5-7.5
[50]	Sewage sludge ash	-					7.2
	Nano Aluminum	-					-
[51]	Sawdust ash	7.23	50.31	9.4	7.23	-	-
	class C fly ash	13.71	29.41	14.66	13.71	>2.4	-
[52]	Quarry dust	14.3	45.4	15.52	6.53	-	-
[53]	Lime sludge	50	7	1	0.8	-	-
[54]	Recycled gypsum	96% $CaSO_4 \cdot 1/2H_2O$					
*[55]	Yeso	33.8	2.1	1.4	0.4	-	-
	Metacaol ń	1	52	40	2.5		

*A clinker with similar properties to Portland cement according to the European standard BS EN197-1 was used.

Nanoparticles, although not cementitious, have a good specific surface area and fast binding with soil particles. In soils of medium plasticity, the use of nano silica and white cement increased soil strength 7 times more with optimal doses; these additives can be used separately to stabilize soils, but the action of both can be adequate to reduce permeability [49]. Other aggregates constituting fine particles such as nano aluminum, in combination with sewage sludge ash and cement, is used to improve stabilization results, specifically, it contributes to the decrease of PI and swelling potential in clayey soils with only 1% in percentage of addition, beyond that, the CBR value tends to reduce because of insufficient water content for reactions in treated soils [50]. The feasibility of stabilizing clayey soils with finely divided aggregates can then be inferred; related to this, sawdust ash (SA) can generate a filling effect as it is made up of very fine particles; and class C fly ash (CFA), a cementitious compound in the presence of water, is studied to reduce the use of cement. A correct dosage is to avoid exceeding the use of a single additive; CFA provides $Ca(OH)_2$ (calcium hydroxide), which reacts inappropriately with the silica and alumina in the SA, reducing strength when one aggregate is used in excess. The increase in OMC is also observed due to the absorption of water from SA and the decrease in silt and clay. With only 1% cement with SA and CFA, the swelling of the expansive soil is reduced; the low percentage of cement was due to the fact that its use was only required to drive the pozzolanic reaction. It is important to mention that the increase in permeability contributes to the decrease in swelling potential because there will be less water to absorb [51]. Also, microparticles of quarry dust (8%), specifically those passing the 0.075 μm sieve combined with cement (6%), can improve lateritic soils classified as low plasticity clay in terms of UCS values, CBR and strength gain due to the development of CSH and CASH gels [52].

The use of chemical additives such as calcium chloride in soils of medium to high plasticity can reduce swelling because it absorbs water; but it decreases bond strength due to salt solubility. As for the use of cement, cement alone forms a very rigid structure at high concentrations, which makes a material not reusable. Adding cement with calcium chloride can counteract the negative effects caused by using each one separately; the cement contributes to maintain a solid structure avoiding the leaching of calcium chloride and together they reduce the intensity of the pores [25].

Lime sludge is a waste from the paper industry with a high calcium content, and was investigated for its influence in stabilizing expansive soils, and to increase its effects, it was combined with cement. Lime sludge is a non-plastic compound, so the plasticity index was reduced and the swelling index decreased by approximately 40%. It was revealed that small amounts of the residue do not react adequately in flocculation; therefore, the MDD was compromised and declined for low percentages of lime sludge. Its incorporation into the soil with considerable proportions of cement (10%) helps in the increase of CBR and UCS values at 28 days of curing [53]. Recycled gypsum, due to its solubility with water, cannot be used directly to treat problematic soils, so its addition together with lime or cement is being studied. The latter is the most suitable for its stability and durability under climatic conditions [54].

There are thresholds between amounts of gypsum to be considered; outside of these the improvement is insufficient or decreases; the decrease of the final water content has been evidenced since the higher the dosage, the more water is consumed for the subsequent chemical reactions; as gypsum represents up to 15% of the Clinker used, the UCS values improve in the less saturated sample; which indicates that the strength gain also depends on the initial moisture content; however, gypsum is effective in stabilizing soft soils with moderate moisture contents mainly due to the creation of ettringite originated from the reaction of clinker and metakaolin with calcium aluminate; ettringite influenced the pore filling effect [55].

2.3.3. Slag and Fly Ash with Non-Traditional Aggregates

Fly ashes are implemented in the stabilization of clayey soils; they can dry wet soils [55]. On the other hand, slags prove to be more effective for strength gain; which is due to high CaO contents, which contribute to the creation of CSH/CA-SH and CASH gels [16].

Fly ash and slag are common additives; additionally, various wastes with reasonable amounts of silica and alumina are available in the waste stream that can be good candidates even for geopolymerization [34]; Table 5 shows the chemical composition of some aggregates used in recent years, which gave good results in stabilization.

A combination of granulated blast furnace slag and calcium carbide slag with desulfurization gypsum can be used to improve soft clayey soils; investigation of the mixture indicates that strength is increased to a greater extent by the slag residue and it performed better than cement. Stability to freeze-thaw cycles was even demonstrated; which is attributed to the densification of the soil by the gels formed, corresponding to CSH and calcium aluminate oxide (CAOH) [56]. Similarly, the LRF reflects a cementitious behavior, where the Atterberg limits improved for additions beyond 5% up to 20% as the optimum LRF content for strength and bearing capacity increase up to 3 and 1.4 times, respectively, according to the UCS and CBR test, the latter due to the increase in MDD [43].

Regarding fly ash, lignite (BCFA) in varying percentages, compaction results indicated the increase of OMC, due to the water absorption capacity of BCFA and hydration for the formation of Ca(OH); which contributes to cation exchange by the dissolution of the same in Ca^{2+} and OH - . MDS increased up to certain concentrations of BCFA (3%) due to pore filling. It is important to mention the improvement in CBR values, accordingly, the maximum CBR was 3.41% for a specific amount of 3% BCFA; then it decreases because of a higher addition that acts as clay thus affecting the cohesion [57]. Also, magnesium oxychloride cement (MOC), which has been previously used to activate GGBS and FA, was evaluated with optimum amounts of FA, namely 3% MOC and 1.5% FA, a choice made based on an adequate ratio in the reduction of swelling and increase of q_u in the UCS test for expansive clayey soils. The most striking effect after stabilization is the reduction or disappearance of macropores due to the decrease in moisture holding capacity [42].

Table 5. Stabilization with slag and/or fly ash with other aggregates

Reference	Aggregate	Chemical Composition (%)				pH
		CaO	SiO_2	Al_2O_3	Fe_2O_3	
[42]	Fly ash CV=FA	-				-
	Magnesium oxychloride cement (MOC)	-				-
[43]	ladle refined furnace slag (LRF)	53.16	24.27	6.38	-	10-11
[56]	Ground granulated blast furnace slag (GGBS)	45.35	43.26	1.87	0.24	-
	Desulfurization gypsum	44.71	29.28	14.85	0.39	-
	Calcium carbide slag	75.48	6.02	7.79	0.51	-
[57]	Brown coal fly ash (BCFA)	3.568	45.265	22.58	7.635	-

2.4. Chemical Stabilization with Residues

The use of residues is a stabilization method that has a positive approach to environmental care and seeks to partially or totally replace lime and cement [27]. It involves the use of combining industrial by-products with natural aggregates to positively affect the physical properties of the soil or act as a cementing agent. The trend in waste research provides solutions to environmental pollution resulting from poor waste disposal management [58].

For stabilization with residues, fine particles are sought in combination with iron oxide, silicon dioxide and aluminum oxide to produce 4 main effects, such as cation exchange, agglomeration, hydration and pozzolanic reactions [48]. Table 6 shows industrial wastes and their chemical composition, which were used in research related to the subject matter proposed in the present review.

Recycled glass (RG) has a positive impact on expansive clayey soils, reducing the swelling potential by 78.9% at 25% of the dry soil weight [27]. Residual glass powder (RGP) can reduce the Atterberg limits as the percentage of addition increases, which is because the (RGP) functions as an internal material and the water absorption capacity of the RGP particles is lower than that of clay particles. RGP helps to decrease voids between particles in the mix and to increase strength and bearing capacity up to 15% addition [24]. Another study indicated the improvement in UCS values related to the friction generated between particles. Flexibility is another benefit, as it generated pores due to the shape and size of the crushed glass [59]. The discrepancy between the benefit of decreasing and generating pores lies in the particle size; while one uses glass powder (82% silt), the other uses crushed glass with particles smaller than 5 mm.

Adding residual marble dust to low plasticity (CL) soils decreases the PI and increases the MDD. With a content of 10% to 20%, and with a focus on road infrastructure, it was indicated that the thickness required for paving decreases by approximately 50%, which translates into economic savings. Additionally, it was shown that it can increase the service life of CL soils by up to 86% [21]. Different proportions of marble powder increase the strength of the CL soil, however, small additions of 3% were necessary to increase the strength by 2.8 times compared to the untreated soil. This aggregate reduces the vertical displacement compressive stress for flexible pavements [60].

In the production of ready-mixed concrete, residues called concrete slurry (CS), composed of hydrated and non-hydrated particles of cement, sand and admixtures, are generated. The alkaline pH and the content of cement residues in this material studied provide positive initial notions for stabilizing clayey soils. It is not necessary to highlight the reaction capacity of CS in comparison with cement, which is lower; however, this effect is beneficial since it amplifies the exchange of sodium and calcium ions, resulting in a decrease in plasticity. Good results were evidenced with an optimum percentage of 8%, contributing in economic and environmental terms where 1 kg of this residue has a stabilization effect equivalent to using 0.380 kg of cement [61].

Table 6. Stabilization with residues and other aggregates

Reference	Aggregate	Chemical Composition (%)				Gs
		CaO	SiO_2	Al_2O_3	Fe_2O_3	
[21]	Marble dust	56.02-56.39	0.08-0.24	0.03-0.08	<0.06	2.30-2.35
[24]	Glass powder	13.3	71.21	1.91	0.45	-
[27]	Recycled glass	-				2.48
[58]	Limestone Dust (LSD)	54.6	1.1	0.35	0.04	2.6
	Sugarcane Bagasse Ash	2.8	72.6	6.4	6.1	1.9
[59]	Crushed glass	14.15	68.14	2.18	0.92	2.64
[60]	Marble dust	4.45	71.18	19.42	3.7	2.64
[61]	Concrete slurry	Cement, sand and other particles				
[62]	Bituminous oil shale ash	48.53	25.06	4.31	1.73	-
[63]	Calcium carbide	68.99	2.84	2.16	0.15	2.32
[64]	Wood ash (WA)	25.1	2.7	14.6	0.2	-
[65]	Quarry fines (QF)	-				2.75
	Cement kiln dust	67.72	11.5	3.1	3.55	-

From the burning of oil shale in the oil or power industry, oil shale ash is produced. Bituminous oil shale ash (OSA) is studied to take advantage of its cementing properties as in fly ash. It is identified that the PI is lower in treated soils and according to the compaction and UCS test, the optimum percentage is between 20% and 25%. The consolidation coefficient decreased with the increase of OSA, a positive effect for designing foundations in civil engineering thanks to the reduction of the settlement rate in primary consolidation; the results also show a decrease in the permeability coefficient with the increase of OSA, being the optimum recommended content for the use of OSA, 20% [62].

The use of sugarcane bagasse ash (SCBA) in combination with limestone powder can reduce the plasticity index of a CL clay soil, because of the calcium and silicon content for cation exchange, and the ashes used, which are non-plastic and replace plastic soil particles. The shrinkage limit decreases, indicating a reduction in the swelling potential, the soil becomes less expansive. SCBA is insufficient to stabilize soils, as its addition to the samples increases, the lower specific gravity (1.9) of the ash replaces the higher specific gravity particles thus reducing the density. The increase in bearing capacity could be due to flocculation-agglomeration caused by cation exchange [58].

In the production of ethylene gas, the residue obtained is calcium carbide (CC). Comparing its viability for stabilizing clayey CL soils with lime, very similar values are obtained for OMS and MDD because their chemical compositions are very similar. Mechanical properties such as CBR value increases 72.1% and 50.3%, after 7 days of curing for CC and lime separately, respectively; it is also 90% more economical than lime for its implementation in soil stabilization for subgrade [63].

Wood ash (WA) decreases the plasticity index and linear shrinkage, thus preventing the soil from expanding and causing fewer cracks; however, WA favors water absorption, which increases LL and plastic limit (PL) values. The compaction results show a decrease in MDD due to the lower specific gravity of the WA. The optimum addition for maximum strength (UCS) and bearing capacity (CBR) values is 24%, void spaces are filled, reducing permeability, and cementitious gel was generated [64]. For organic clayey soils classified as CH, cement kiln dust (CKD), which is the by-product of a cement factory, and quarry fines (QF) sieved with the No. 4 sieve were studied. The study reflected a decrease in LL and PI with increasing CKD. Dry unit weight increased and OMC decreased with curing time. In strength, a more pronounced increase was recorded from day 14 to day 28 in the UCS values, the delay evidenced in the first days may be justified by the necessary induction period for pozzolanic reactions [65].

3. Discussions

This section will include a description of the results obtained in the different investigations regarding soil stabilization properties including clay/silt/sand content, LL, PL, PI, optimum moisture content, maximum dry density; in addition to the optimum aggregate content required, the positive economic implications of implementing some investigations in soil stabilization and their importance.

3.1. Properties of Stabilized Soils

Table 7 includes specific values from the articles reviewed, in order to provide clarity on the type of soil that was improved.

For black cotton soils, using plastic sheeting at two depths improved the bearing capacity, the mechanism of improvement is not reported [1]. Black cotton soil swells excessively, being unsuitable for construction due to the presence of montmorillonite, kaolinite among others [8].

In lime stabilization, the use of a natural pozzolan converts the clayey soil to silty soil and samples suitable for use in subgrade were evidenced due to pozzolanic reactions and a change in morphology by the generation of CSH and CASH gels. The improvements indicate that its use can be satisfactory for severe environmental conditions; also with the use of PET fibers the lime-treated soil presented an additional improvement [2] [19] [19] also taking into account soils with expansion potential [20]; these soils present an improvement in shear strength with coconut fiber and lime geotextile [38]. Soils treated with fibers and alkaline binders have a higher safety factor and CBR values [36] guaranteeing durability in expansive soil [39].

When cellulose fibers are used, they expand because they absorb water, creating a bond between soil particles, i.e., cohesion [8]. With sawdust and rice husk fibers, better settlement characteristics and lower compressibility are achieved; it is also mentioned that they can serve as drainage in subgrade layers due to the hydraulic parameters studied [18].

For low temperature environments, geopolymerization may not be as effective, comparing a curing at 20 ℃, -2 ℃, -10 ℃; in the last two the strength decreases by more than 60%. Still, the results are better than the traditional implementation of cement stabilization [15]. For soils contaminated with sulfates, tests with magnesium sulfate are applied; geopolymerization being a suitable treatment [32]; which is enhanced if the mechanochemical methodology is applied [16] [30].

3.2. Optimum Aggregate Content

3.2.1. For Geopolymerization

Table 8 contains the aggregate used, as well as the amount or molarity of the alkaline activator. Additionally, the cementitious gels formed by scanning electron microscopy (SEM) analysis are included.

Freezing in stabilization by geopolymerization decreases its efficiency due to the formation of ice crystals, which expand generating cracks; UCS values can decrease with the activator, copper slag [15].

With the use of slag and fly ash, added in samples together or separately, the effectiveness of slag over fly ash was demonstrated, since it undergoes a lower mass change under sulfate attack and presented higher UCS resistance [16]. The reaction rate has an impact on the density of the samples, this possible reason presents in the use of different molarities, when the limit is exceeded, a drop in density is evidenced [28].

In sulfates, the sulfate attack test shows that with prolonged immersion sulfate entering by capillary adsorption to neutralize the CAH gel and forming the ettringite, expansive crystal, the main reason would be the high calcium content, which dissolves in the sulfate solution; all with cement stabilization; however, in geopolymerization with slag and fly ash, the samples remain complete with microcracks and present higher strength after immersion [32]. An improvement of ductility in geopolymerized specimens is reported to outperform fly ash stabilized specimens [34].

Table 8 shows different contents of additives with molarities and amounts of alkalis; the variance lies in the reactivity of the materials used; if it is lower, the molarity/content is increased; in this way a suitable environment is established for pozzolanic reactions and the formation of cementitious gels.

Table 7. Propiedades de los suelos estabilizados

Reference	Clay (%)	Silt (%)	Sand (%)	LL (%)	PL (%)	PI (%)	OMC (%)	MDD (kg/m^3)	SUCS
[1]				67	43.75	23.25	22	1590.757	C
[2]				58.8	30	28.8	27	1509.1799	CH
[8]				103.4	25.7	77.7	29		
[15]	-	-	-	28.38	15.21	13.17	13.41	1890	CL
[16]	58	32	-	41	25	16	19.2	1784.503	CL
[18]	79.6		20.4	65	35	30	27	1900	CH
[19]	45.3	29.5	25.2	39	17	22	14.5	1780	CL
[20]				88.5	43.6	44.9			CH
[21]	27	16	19	42.2	21.6	20.6			CL
	47	26	21	46	20.6	25.4			CL
[22]	87	9	4	65	22	43	18.9	1672.33	CH
[23]				57.9	21.7	36.2	25.1	1618.1	CH
[24]	47	34	19	44.2	24.81	19.39	18.5	1740	CL
[25]				130-150	60-70	70-80	32-40%	1172-1223	CH
[26]				55.76	34.25	21.51	23		OH
				51.17	34.10	17.07	34		MH
[27]	97.5	27	2.5	60	24.4	35.6	22.3	1460	CH
[28]				249.94	40.21	209.73	34	1314.98	CH
[30]	99	-	-	53	27	26	-	-	CH
[31]	68	29	3	57	26	31	23.6	1570.363	CH
[32]				49.9	25.8	24.1			
[33]				31.5	13.21	18.29	17.5	1760.030	CL
[34]	48	42	10	56.8	23.8	33			CH
[35]	13.5	82	4.5	41.7	27.5	14.2	20	1680	CL
[36]				66					CH
[37]	62.1	32.1	5.8	55.87	27.43	28.44	24.46	1583	CH
[38]	71.5	24.5	4	89	47	42			CH
[39]	71.5	24.5	4	89	47	42	19.2	1799.79	CH
[40]	43	37	20	44	22	22	19.5		CI
[41]				58	32.9	25.1	24	1496	
[42]	55	43	2	65	25	40			CH
[43]				41.32	21.8	19.52	16.50	1770	CL

Table 7 continued

[44]	61.5	35.24	3.26	75	34	41	30	1402	CH
[46]				79.6	31.41	48.19	34.06	1230	CH
[47]									CL
[48]				43	22	21			CL
[49]	38.1	36.5	24.2	36	22	14	14	1930	CL
[50]				33 - 33.3		11.8-12.2	15-15.5		CL
[51]				55.01	23	32	23.18	1690	CH
[52]				42.6	24.06	18.54			CL
[53]	36	41.5	22.5	84	26	58	29.83	1353.163	CH
[54]	18.9	55.4	25.7	100	61.5	38.5			CH
[55]	49.7	49.1	1.2	46.2	25.3	20.9			CL
[56]				43.5	22.6	20.9	21.4	1780	CL
[57]	67.3	32.7	-	67.9	27.72	35	19.27	1560	CH
[58]				38.44	23.24	15.2	24.5	1740	CL
[59]	67.1	24.2	8.8	52.29	18.44	33.85	24.9	1460	CH
[60]				43	16	27	21	1600	CL
[61]				37.6	19.8	17.8	13	1930	CL
[62]	71	23.7	5.2	77	33	44	30.1	1464.312	CH
[63]	13.6	83.9	2.5	37.8	19.9	17.9			CL
[64]	52	28	15	45.1	25.18	19.92	19.2	1780	CL
[65]				85	46.91	38.09			CH

Table 8. Optimum additive content for geopolymerization

Reference	Aggregate	Optimum Content	Alkali Content or Molarity	Scanning Electron Microscopy (SEM)
[15]	Metakaolin	10%	6%	CSH and CAH
[16]	Ground granulated blast furnace slag	25%	2.5 M	Lattice CASH and laminar CSH
	Class F fly ash	0%		
[28]	Wastepaper sludge ash	30%	12 M	NASH and CASH
[30]	Ground granulated blast furnace slag	20%	14M	NASH
	Class F fly ash			
[31]	Ground granulated blast furnace slag	16%	10%	-
	Ordinary Portland cement	4%		
[32]	Ground granulated blast furnace slag	25% with a 9:1 ratio	25%	CSH and CASH
	Fly ash			
[33]	Class C fly ash	10%	20%	C/NASH
	Class F fly ash			
	Ground granulated blast furnace slag			
[34]	Bagasse ash	20%	12M	C/NASH
	Quarry dust			
[35]	Recycled glass powder	5%	5M	Alumina-silicate structure
	Copper slag			

3.2.2. For Reinforcement Use

Table 9 lists the optimum reinforcement contents and important data regarding soil stabilization achievements.

The cellulose-based fibers used have a positive impact on the soil in terms of strength and stability [8]. Natural fibers can be treated with citric acid, where soaking for 24 h can be considered [18].

Another alternative is polyethylene terephthalate (PET) fibers. Used in a soil treated or not with lime, they have a good performance in point load resistance and flexibility [19]; and it is effective in reducing swelling in expansive soils [20]; for lime-treated soils, tire waste is also used, and due to its hydrophobic property and lower Gs, OMC and MDD values decrease [40]. Also the use of pozzolans, an alkali and fibers, showed greater improvements than using only lime with polypropylene fibers [36].

Table 9 gathers the reinforcement additions, of which, in the case of the inorganic ones, they do not represent a large percentage of the dry soil weight, being less than 2% in all cases.

Table 9. Contenido óptimo de refuerzos

Reference	Reinforcement	Optimum Content	Important data
[1]	Plastic sheets	-	Sheets are used at two different depths
[8]	Bamboo	15% (300 μm)	Increases UCS values by more than 50%.
	Rice husk	15% (300 μm)	Reduces PI
	Straw fibers	15% (150 μm)	Reduces free swelling in expansive soils
[18]	Saw dust	6%	The fiber was treated with citric acid
[19]	Plastic Polyethylene Terephthalate (PET)	1.5%	The lower specific gravity decreases OMC and MDD values
[20]	Solid plastic wastes	2%	An appropriate size of 8 x 15 mm is desirable to improve UCS, CBR values and swelling potential
[36]	Polypropylene	0.5%	The fibers were used together with an alkaline binder based on steel slag and sugarcane bagasse ash
[37]	PET	1%	The bridging effect reduces cracks, unlike untreated samples, which showed shear failure due to loss of cohesion
[38]	Coir geotextile	-	It is placed half and one third of the sample depth 10 mm thick fibers
[39]	Polypropylene	0.5%	Pond ash and fiber are used, the former for chemical stabilization and the latter for reinforcement against cracking
[40]	Tire-derived aggregate	5%	As TDA size increases, UCS values increase; but it is also influenced by curing time and another stabilizer, in this case, lime
[41]	Plastic strips	0.75%	Increased plastic fibers improve CBR values, in addition to reducing swelling

Table 10. Optimum lime content with other aggregates

Reference	Aggregate	Optimum Content	Lime	Important Data
[2]	Natural pozzolana	20%	8%	A lower PI is obtained, considering a lime-stabilized soil
[23]	Igneous Rock: granite and rhyolite	32%	6%	Rhyolite powder showed better results than granite powder
[44]	Phosphogypsum	30%	4%	UCS improves up to 7 times
[46]	Waste ceramic dust	15%	4%	These percentages meet the regulatory requirements for road construction on CH soil
[47]	Glass fiber	1%	6%	The strength improvement factor increases with only 1% glass fiber and 6% lime

3.2.3. For Use of Lime with Other Aggregates

Table 10 mentions the optimum aggregate and lime content, as well as important data.

Studies reveal an improved internal structure; thanks to electron microscopy and X-ray analysis, better flocculation could be observed in clay samples [2].

The igneous rocks used for lime stabilization have an impact on IP reduction because they contain quartz, a mineral that does not absorb water [23].

Despite stabilization with phosphogypsum, it is pointed out that this aggregate reduces pH values because it is acidic, which is not favorable for forming cementitious gels since it does not adequately dissolve the silicon and aluminum of the soil studied [44].

It is mentioned that, in the treatment of the soil with lime, it causes the MDD to decrease, while the residual ceramic powder counteracts this action [46].

Due to the plan to reduce the use of lime, other aggregates are used, presenting varied results; in the case of using rock dust, the percentage can exceed 20%.

3.2.4. For Use of Cement with Other Aggregates

Table 11 includes data on the optimum aggregate and cement content, as well as some relevant mechanisms and data.

The use of firewood ash helps to improve the strength of the soil, which can be attributed to the filling of voids, improving the microstructure, in addition to the pozzolanic activity identified in the aggregate, rated as good [48].

With the use of nano aluminum, more water is needed to reach the optimum moisture content, in addition, the MDD decreases, which is why the optimum content was set at 1% [50].

It could be observed that, as in the use of lime with other aggregates, the cement was used with different proportions of the same; it was evidenced that minimal additions also contributed to the strength gain.

3.2.5. For the Use of Slag and/or Fly Ash with Other Aggregates

Table 12 includes values for the optimum aggregate content of fly ash and/or slag, which is an industrial waste.

Additionally, it is shown that the content of fly ash and different types of slag varies, without following a specific pattern.

3.2.6. For the Use of Waste and Other Aggregates

Table 13 specifies the optimum amounts of residues and other aggregates and some important research data.

The varying values of additions of different aggregates may be due to the different types of soils to be stabilized. It is necessary to emphasize that this review does not offer a concise value for implementation in the field; however, it provides notions of what was used and had good results; thus, future research incorporating new variables is foreseen.

Table 11. Optimum cement content with other aggregates

Reference	Aggregate	Optimum Content	Cement	Important Data
[25]	Calcium chloride	4-8%	2%	The calcium chloride is soluble, so it combines with cement
[26]	Rice husk ash	9% to improve CBR	3% (CBR)	Samples with 1 cm of sand thickness and without sand were considered
[48]	Firewood Ash	2%	8%	Clearly, the exclusive use of cement presents the best strength; however, firewood ash slightly improves ductility
[49]	Nano silica	2%	3%	The optimal dosage of each one separately is 7%
[50]	Sewage sludge ash	15%		The addition of Nano aluminum reduces the plasticity index
	Nano Aluminum	1%	-	
[51]	Sawdust ash	10% at a 30:70 ratio	1%	The liquid limit is reduced, as is the plasticity index
	class C fly ash			
[53]	Lime sludge	12%	10%	Increased UCS value and maximum dry density due to cement
[54]	Recycled gypsum	22.5% at a ratio of 1:1 to 2:1		Stabilization that proved to be resistant to soaking effects
[55]*	Yeso	1.8%	12%	Greater rigidity, but greater fragility
	Metacaol ń	3%		

Table 12. Optimum slag and/or fly ash content with other aggregates

Reference	Aggregate	Optimum Content	Important Data
[42]	Fly ash CV=FA	1.5%	It reduces water holding capacity and performs well in expansive soils
	Magnesium oxychloride cement (MOC)	3%	
[43]	ladle refined furnace slag (LRF)	20%	The MDD and optimum moisture content increases with the addition of aggregate
[56]	Ground granulated blast furnace slag (GGBS)	10%	Good freezing performance
	Desulfurization gypsum	2%	
	Calcium carbide slag	6%	
[57]	Brown coal fly ash (BCFA)	3%	Reduction of porosity and increase of optimum moisture content due to water absorption property

Table 13. Optimum cement content with other aggregates

Reference	Aggregate	Optimum Content	Important Content
[21]	Marble dust	10%-20%	Increases the life span of clay soils by more than 80%
[24]	Glass powder	15%	The values of the Atterberg limits decrease with the residual
[27]	Recycled glass	25%	-
[58]	Limestone Dust (LSD)	15%	-
	Sugarcane Bagasse Ash		
[59]	Crushed glass	10%-15%	Improvement of UCS values, decrease of optimum moisture content
[60]	Marble dust	3%	There was evidence of reduced vertical deformations and reduced PI
[61]	Concrete slurry	8%	1 kg of this aggregate is equivalent to approximately 300 g of cement
[62]	Bituminous oil shale ash	20%	Lower values in Atterberg limits.
[63]	Calcium carbide	5%	Higher bearing capacity in contrast to samples stabilized with quicklime
[64]	Wood ash (WA)	24%	Increased strength and load capacity
[65]	Quarry fines (QF)	10%	Increases performance with longer curing times.
	Cement kiln dust	16%	

3.3. Economic Implications and Environmental Impacts

The use of waste plastic sheets is an economic stabilization option in addition to a good final disposal of the waste [1].

Emphasis is placed on the use of fibers constituting a waste, which can be detrimental to the ecosystem as they are produced in huge quantities year after year bringing global accumulation [8]. The use of fibers leads to a more efficient construction process due to improved plasticity and compaction, which is an economic benefit; not only that, but economic benefits are highlighted as materials that end up as waste such as, for example, used plastic bottles, synthetic geo based on coconut fiber, plastic with waste brick dust [18] [19] [19] [20] [38].

An improvement in the reduction of carbon emissions in geopolymerization by more than 35% compared to cement using paper sludge ash is reported [28].

In economic terms the stabilization by replacing traditional additives with those presented in this review are very beneficial; it is reported that, through waste management, the implementation of geopolymerization of a 1 km double lane road allows the reuse of more than 1000 tons of miscellaneous waste [34].

Regarding the use of lime, an amount of 10% would not be economical and neither would it substantially benefit stabilization [34]; therefore, most studies incorporate this additive in smaller proportions and partially replace it with waste, thus becoming cost-effective.

3.4. Importance

It is usually not economically profitable to remove the deficient soil, as it generates additional costs in construction [41]. With the rapid growth of infrastructure, it is necessary to look for effective and cost-effective additives; normally, mechanical stabilization is used where soils are transported to a given area; instead, stabilization with additives is proposed [1].

The use of natural pozzolans (NPs) is recommended in lime-stabilized soils, because while lime reduced the MDS, NPs compensate [2].

Future studies could provide emphasis on long-term performance and durability factors in stabilization with cellulose fibers because it was feasible to implement them in deficient soils, and depending on what is to be achieved, use different types of fibers [8].

An important aspect is the study of fibers in soils treated or not with lime; in addition to the shape and percentage of the fibers, demonstrating that the form in strips has an improved impact compared to granules [19]. Even the use of plastic was beneficial to reduce the pavement layer, being important for light constructions [20].

When there is excessive loading, due to vehicle loading, in clayey soils with tendency to expansion, it is necessary to improve the differential settlement, so an alkaline binder and polypropylene fibers are convenient, and compared with fibers and lime, greater resistance is achieved [36]. Since lime is a traditional additive, it is necessary to study it with fibers, and this is what is done by analyzing its contributions to the soil, such as, for example, tire waste, of which not even 10% is recycled in countries such as Australia [40]. In addition, the analysis of PET fibers under freeze-thaw cycles, characteristic of cold areas, was deepened, here high values of resistance and resilient modulus could be evidenced after different cycles [37] [39]. It should be considered that when fibers are used with lime, the latter can be leached due to different situations such as flooding, but in the case of a subgrade for a pavement, it is not a main concern [40].

On the other hand, in different parts of the world there are cold climates and in frozen soils, geopolymerization is effective, although the resistance decreases, it is still more effective than cement [15]. Normally, a traditional method is used that involves the dangerous handling of alkalis; in order to reduce the risk, an alternative method is proposed, a necessary action to improve its practicality and environmental sustainability; in this way its implementation is generalized in construction [16].

4. Conclusions

This bibliographic review contemplated the studies carried out for the stabilization of clayey soils by geopolymerization, reinforcement, use of traditional additives with other aggregates; and residues.

In geopolymerization, it is important to take into account the incorporation of precursors mainly with silica and alumina to obtain a solid structure of the clay soil thanks to the cementitious gels generated, either CHS/A or C/NASH in an alkaline environment produced by two alkalis NaOH and Na_2SiO_3 in the presence of humidity, obtaining better results but increasing the difficulty in its application in contrast to using only one activator. The temperature and curing time can be varied always taking into account that with the increase of these, better results were evidenced. Geopolymerization has proven to be effective in stabilizing expansive soils and soils with sulfates, the latter taking into account the chemical composition of the precursor.

Fibers in stabilization are generally used to improve mechanical properties as they can decrease the MDD due to their specific gravity, which in most cases is lower than that of the soil. The advantage of plastic fibers is that they are not affected by temperature compared to geopolymerization and can form a stabilized soil with fewer cracks due to the friction or bonding they exert between particles. The inclusion of other fiber composites is implemented to further increase the strength. The use of organic fibers is also contemplated, taking into consideration their previous treatment to prevent them from degrading.

In traditional stabilization with other non-traditional aggregates, lime, cement, fly ash and slag were evaluated. It is known that these additives are used for their effectiveness in reducing the PI, which is related to the workability of the soil, by improving the mechanical properties through the formation of cementitious gels; and in relation to FA and slag, they are used because of their low cost and to take advantage of industrial waste.

Lime, on the other hand, decreases MDD and increases OMC, so non-traditional aggregates were used to counteract this. Although it does not improve physical properties, lime can improve CBR values. An alternative to waste disposal is usually sought by incorporating it along with lime in stabilization.

Regarding cement, it does not decrease the MDD as lime does, but curing in humid conditions is necessary for better results due to the hydration necessary to produce cementitious gels. Cement is mainly used to increase mechanical properties such as strength and bearing capacity, to counteract side effects of other aggregates or even to support reactivity.

Fly ash and slag are used in combination or with other aggregates to contribute to soil improvement by generating cementitious and cation exchange agents. The high CaO content in slag provides higher strength than fly ash, making it ideal for increasing values in UCS and CBR tests. Fly ash also has a positive impact on mechanical properties, but tends to absorb water, which increases OMC.

Finally, residues in stabilization have a focus on improving physical properties, increasing the MDD of clayey soils when the specific gravity of the residues is higher; in addition to reducing the PI, pores are reduced when smaller-sized residues are used.

Thus, it is concluded that the literature review provides the necessary scope to incorporate non-traditional aggregates in soil stabilization, either by geopolymerization, using alkalis; reinforcement, to improve flexibility; with other common additives, to improve their results and reduce the consumption of lime and/or cement; and residues, through the partial replacement of soil particles, improving their workability and density.

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